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"Theoretical and Experimental Investigations of Extremely Dense Plasmas
at Very High Energy Densities"

UNPUBLISHED PRELIMINARY DATA

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RESUME OF WORK PREVIOUSLY REPORTED


Facilities were designed and constructed to produce an extremely dense plasma and measure its properties. The high-pressure, transient plasma is confined by water. A chemical explosive, PETN, compresses the water to a pressure of 10^5 atmospheres with a decay time constant of approximately 2 microseconds. The plasma is produced by electrically exploding a wire located in the compressed water. A sequence of two photographs of the plasma is taken with a double Kerr cell camera to show growth characteristics of the plasma.

Construction of the timing controls and instrumentation was completed at about the time of the previous report in October, 1963. Frequent malfunctions during operation have made further work necessary to improve the reliability of the equipment, but no functional changes have been required.

EXPERIMENTAL WORK

Since the last report, numerous Kerr cell photographs have been taken. These photographs show the plasma to be considerably different from what was expected. Previous University of Michigan experiments have shown that when a wire is exploded under water by a capacitor discharge, a symmetrical, cylindrical plasma column is formed. A similar type of cylindrical channel was expected when the water was pre-compressed by a chemical explosive, but the observed behavior was entirely different. The plasma formed into strings of luminous, globular segments, which grew in an unstable manner.

The original plans to measure the properties of the plasma assumed that it would exist as a homogeneous, cylindrical region. However,



measurements are not feasible with the irregular conditions which actually exist unless some other techniques can be devised. Possibly, the nature of the irregularities observed will be a source of information about such quantities as temperature and conductivity.

Photographs were taken for various rates of current rise and for various explosive pressures. In all cases the discharge electrodes were 0.1" apart, and they were bridged by a 0.001"-diameter tungsten wire. Without exception the photographs show the globular, luminous regions.

A sequence of photographs (10X enlargements) for a plasma in uncompressed water is shown in Figure 1. The discharge was from a 15-microfarad capacitor charged to 12 kilovolts with a current maximum at 1.8 microseconds. The cylindrical spark channel grew radially in time as the current increased. The images at the ends of the channel are reflections from the electrodes.

Other photographs shown in Figures 2 through 5 are for the same conditions as in Figure 1, except that the discharge was in water which had been compressed by a shock wave from detonating PETN. Figure 2 shows a sequence where the growth of irregularities can be observed. The three bubble-like structures occurred only in this sequence and may have been caused by air bubbles which formed on the initiating wire. Figure 3 shows another sequence where once again the growth of irregularities can be observed. Figures 4 and 5 are two single photographs which illustrate early stages of plasma formation.

ANALYSIS

The causes of the growth of the globular regions of plasma might be explained by two hypotheses. The growth might be primarily due to expansion of hot pockets of plasma, or it might be due to the growth of

relatively cool regions of highly conductive fluid. It is probable that both effects play some part in the plasma growth which is observed.

The explanation of the plasma behavior appears to depend upon the effects of particle interactions which are very important because of the high densities existing in the plasmas. Various theories for high-density plasmas attempt to account for these effects, but they have limitations which prevent them from being applied to the conditions of interest in this case. Yet some insight can still be obtained by studying them.

Equation of State

An equation of state for the plasma was derived from the concept of the Debye-Hückel shielding distance. The equation is not new, nor is it adequate, but the derivation gives insight into the requirements for a more adequate equation and into the limitations of the present one. The derivation starts from the classical Virial theorem and uses the Boltzmann factor with Poisson's equation to compute charge distribution around an ion. This result is used to obtain the following equation for a fully ionized hydrogen-like plasma:

$$2 n_i kT = P + \frac{\sqrt{8\pi}}{3} \left(\frac{n_i}{4\pi\epsilon_0} \right)^{3/2} \frac{|q|^3}{\sqrt{KT}} \quad (mks)$$

where n_i is ion density, ϵ_0 is permittivity of free space, and q is electron charge.

The principal assumption in the derivation is that the kinetic energy of a particle is large compared with the potential energy of particle interactions. Numerically, this means that $T \geq 10^6$, whereas it is nearer $10^{40}K$ for the plasma of interest. For $n_i = 10^{28} m^{-3}$ and $T = 2 \times 10^{40}K$, which are conditions likely to exist in the plasma, the right-hand term is $1.11 \times 10^{10} \text{ nt} / m^2$, where $2 n_i kT = 0.542 \times 10^{10} \text{ nt} / m^2$.

Thus, the equation certainly is not valid for $T = 2 \times 10^4 \text{ } ^\circ\text{K}$, but it does become reasonable if T is raised to $10^6 \text{ } ^\circ\text{K}$. For lower particle densities, the restriction on temperature can be relaxed because interparticle forces are not so significant.

For the condition of 10^{28} m^{-3} and $2 \times 10^4 \text{ } ^\circ\text{K}$, the temperature is not high enough to produce complete ionization and yet the density is so high that interparticle forces cause electrons to be free to drift. Although in general, plasma temperature increases with density, this rule no longer appears to be valid when ionization caused by high density is important.

Various papers in the literature consider methods of calculating an equation of state which extend somewhat beyond the limits of the Debye-Huckel theory but which are still restricted by the condition that temperature be not too low.

Conductivity

A calculation of conductivity of a plasma which was found in the literature is based on the Debye-Hückel shielding theory and has in the denominator an expression $\ln \left[C \left(\frac{T^3}{n_i} \right)^{\frac{1}{2}} \right]$. When the bracketed expression is less than or equal to 1, as is the case for the plasma of interest, then the expression for conductivity becomes meaningless. No better theories have been found for conductivity.

Ionization of Plasma

Saha's equation in its modern form has been widely applied to predict the fraction of particles which are ionized as a function of temperature and particle density. As density increases, the fraction decreases if temperature is held constant until a certain critical density, where interparticle forces have the effect of reducing the ionization potential of an atom. Then, the trend reverses so that a

further increase in density causes an increase in the fraction. To account for this effect a correction term is subtracted from the ionization potential.

The limit of applicability of Saha's equation is reached when the correction term becomes the same order of magnitude as the ionization potential. The author of a paper found in the literature ignores this limitation and even lets the correction become several times as large. In doing so, he predicts a discontinuous upward transition in the fraction of ionization as density is increased at constant temperature. The actual occurrence of this transition is dubious; yet it is known that there is a rapid increase in the fraction as density increases above the critical value.

Any attempt to extend Saha's equation to higher densities for a plasma seems fruitless because the concept of a bound state loses meaning when particles are so dense that several are interacting strongly at any given time.

For a plasma consisting of two parts hydrogen and one part oxygen, the fraction of ionization has been computed for various particle densities and temperatures. The results, shown in Figure 6, illustrate the previously described variation of the fraction of ionization with particle density.

FUTURE WORK

At the present state of the research program the work could proceed in either of two interesting directions.

1. The new and unexpected phenomena in water can be studied further and methods can presumably be devised to measure many of the properties of this type of plasma.

2. The phenomena associated with the water can be by-passed as extraneous, and confining media other than water might be found which will permit the investigation to proceed as originally planned.

Tests currently in progress use an initiating wire much larger than the 0.001" tungsten wire which has been used until recently. This larger wire is expected to produce a plasma derived from metal instead of from water, and it may provide new information about the plasma irregularities. Preliminary tests are also planned using other confining media. The results of these tests will provide a better prospective as to the most realistic objectives for the present contract.

Submitted by

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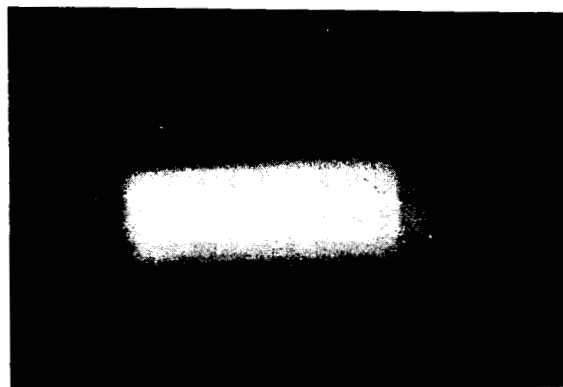
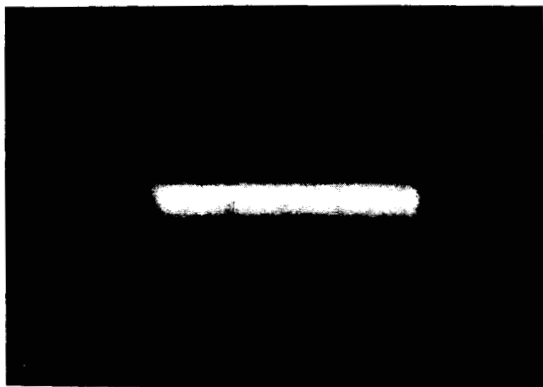


Fig. 1. Two Kerr cell photographs of an electrically exploded wire in water when no chemical explosive was used. The photographs were taken at 0.1 and 0.5 microseconds after start of current flow.

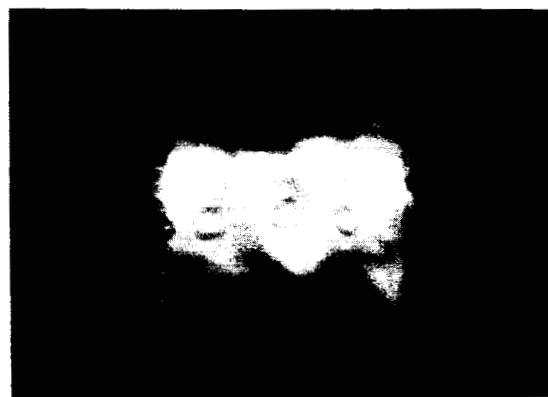


Fig. 2. Two Kerr cell photographs of an exploding wire in water which was shock-compressed by PETN, at 0.2 and 0.6 microseconds after start of current flow.

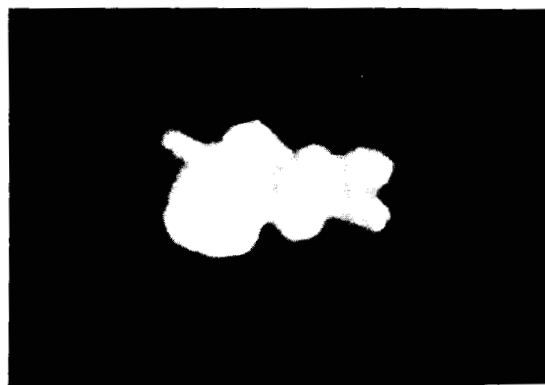


Fig. 3. Same as Fig. 2. with times of 0.1 and 0.5 microseconds.

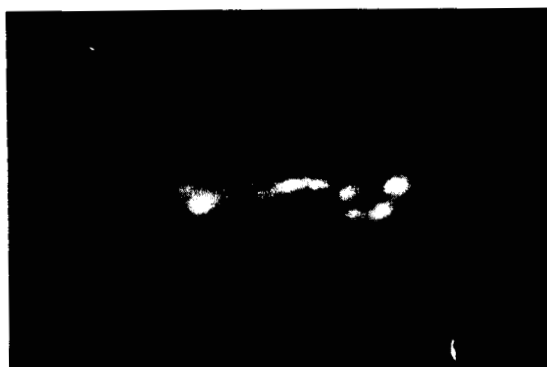


Fig. 4. Single photograph at 0.1 microsecond for same conditions as in Fig. 2.

Fig. 5. Same as Fig. 4.

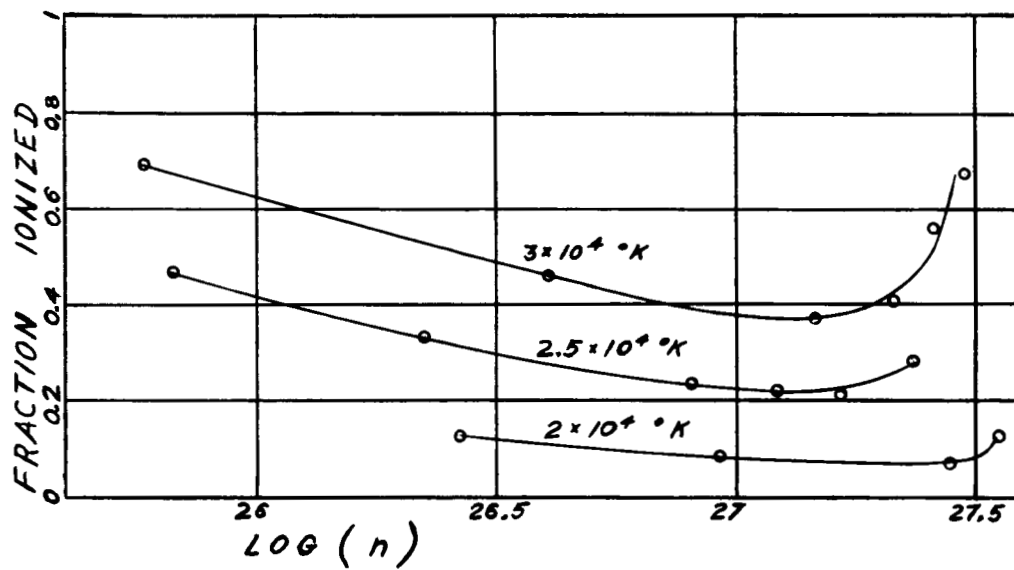


Fig. 6. Fraction of ionized atoms as a function of $\log(n)$, where "n" is the density of all atoms, both neutral and ionized, for a water plasma at various temperatures.